

An Ultra-High-Performance Wideband Reflective Frequency Selective Surface for Linear y to x Polarization Conversion Suitable for Target Detection Systems

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ABSTRACT: This manuscript presents a novel compact reflective frequency-selective surface (FSS) for wideband polarization conversion, enabling efficient polarization manipulation over the frequency range of 8.2 GHz to 9.5 GHz, which is the X-band spectrum for electromagnetic applications. The proposed FSS consists of a metallic pattern printed on an FR4 substrate with a relative permittivity of $\epsilon_r = 4.4$, loss tangent of $\tan \delta = 0.02$, and thickness of 1.6 mm, backed by a ground plane. This configuration enables reflective-mode operation with a tunable frequency range typically spanning X-band, achieved by optimizing the unit cell's geometrical parameters. The proposed structure provides efficient linear-to-orthogonal polarization conversion over 8.2–9.5 GHz (1.3 GHz bandwidth, center frequency of 8.85 GHz), with a polarization conversion ratio (PCR) exceeding 98%. This frequency range lies within the X-band and provides a fractional bandwidth of approximately 14.69. Under oblique incidence, the proposed FSS maintains a PCR above 90% up to 40° , with only a slight bandwidth reduction, and shows good agreement between simulated and measured results. Owing to its compact nature, excellent angular stability and wide operating bandwidth, the proposed FSS is suitable for radar and wireless communication applications.

1. INTRODUCTION

Recently, frequency-selective surfaces (FSSs) [1] have received considerable attention owing to their compact size and planar structure. These two-dimensional artificial surfaces can control electromagnetic waves as transmissive or reflective surfaces and have been extensively used in microwave and X-band applications, such as wavefront transformation, antenna design, radar sensing [2, 3], and imaging. Reflective FSSs provide efficient linear polarization conversion, which is essential for advanced radar target detection [4]. The compact wideband reflective frequency selective surface (FSS) structure provides high-efficiency linear X -to-linear Y polarization conversion [5], improving reception of cross-polarized signals [6], and target resolution in X-band [7] radar applications.

The rapid development of modern radar and surveillance technologies has increased the need for compact and efficient electromagnetic structures that can accurately control electromagnetic waves. Specifically, X-band (8–12 GHz) radar technology is widely employed in target detection, tracking, marine navigation, and military surveillance applications owing to its high resolution and ability to penetrate the atmosphere. Polar-

ization control [8–10] in the X-band frequency range is essential for improving management of the radar cross-section (RCS) and reducing unwanted clutter.

The proposed configuration therefore provides a simple, low cost FR-4-based polarization manipulation FSS designs which have been identified as an effective technology for controlling the transmission and reflection properties of electromagnetic waves. An FSS is a 2-D array of resonant elements [11] that can be designed to modify the phase, amplitude, and polarization of incident electromagnetic waves [12]. Reflective-type [13] FSS designs with metallic ground planes are preferred for radar applications owing to their high reflection efficiency and ability to facilitate polarization conversion [14]. Polarization conversion [15], particularly linear-to-linear polarization [16], is in high demand in radar-based target detection systems.

Converting an incident linear x -polarized wave into a scattered linear y -polarized wave increases cross-polarized scattering, sensitivity, and polarization diversity [17]. However, most traditional polarization converters work at low bandwidths or require complex multilayer designs [18], which are not preferable for RCS reduction [19]. To address the issues, this study presents a high-performance compact wideband [20] reflective frequency selective surface for efficient linear x to y polariza-

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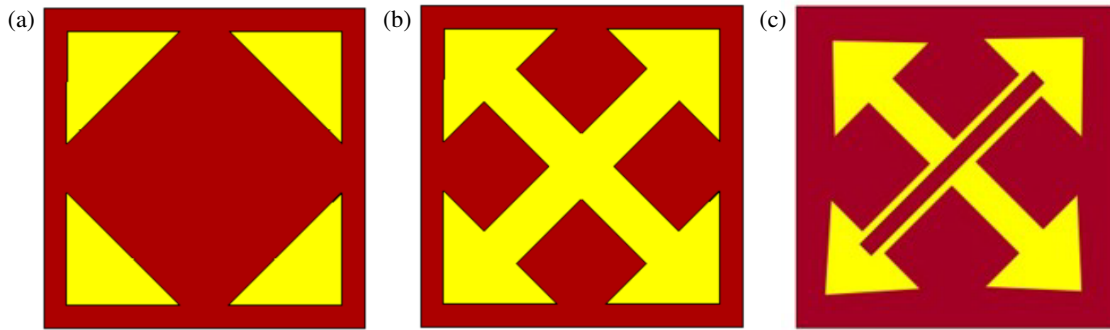


FIGURE 1. Evolutionary stages of the reported FSS design analysis.

tion rotation in the X-band frequency range. The proposed design includes an anisotropic resonator [21–23] on a substrate with a metallic ground plane, which assists in obtaining strong coupling field between the orthogonal electric field components. By optimizing the unit cell's geometrical parameters, wideband cross-polarized reflection [24, 25] with reduced co-polarized reflection can be achieved. The compact unit cell design [26] facilitates simplicity, a low profile, and ease of fabrication, which are preferable for application in radar target detection systems [27].

The novelty of the proposed FSS lies in the combined use of arrow-shaped resonators and a diagonal strip to realize high-efficiency reflective linear-to-orthogonal polarization conversion in the X-band. Unlike conventional single-resonant configurations, the arrow-shaped elements establish the primary resonant response, while the diagonal strip modifies the effective current path and electromagnetic coupling between the resonant elements. The resulting inductive and capacitive interactions enhance cross-polarized reflection over the desired operating band. The optimized FSS achieves a PCR exceeding 98% from 8.2 to 9.5 GHz, corresponding to a fractional bandwidth of 14.69%, while maintaining stable performance up to 40° oblique incidence. The proposed configuration therefore provides a simple, low cost, FR-4-based polarization manipulation design with potential applicability to polarization-diverse X-band radar and target-sensing systems.

This manuscript is organized as follows. Section 1 highlights the introduction and motivation behind the proposed FSS as a reflective linear-to-orthogonal polarization converter. Section 2 describes the experimental analysis of the proposed design and its methodology, followed by simulation results with a discussion of its polarization-conversion performance. Section 3 investigates the geometrical parameters and oblique incidence on polarization-conversion performance. Section 4 explains the polarization conversion mechanism using surface-current distribution analysis. Section 5 describes the fabrication and experimental characterization validation of the proposed FSS. A performance comparison table with recently reported FSS is presented. Finally, the paper concludes with a summary of key findings and contributions.

2. EXPERIMENTAL ANALYSIS OF PROPOSED FSS DESIGN AND ITS METHODOLOGY

The initial configuration exhibits a nearly symmetric response and therefore provides insufficient anisotropy. The arrow-shaped resonator arms [28, 29] and diagonal strip provide inductive current paths, while the narrow gaps introduce capacitive coupling through charge accumulation. Their combined LC response generates resonant modes, whereas the diagonal asymmetry enhances cross-polarized reflection. The proposed FSS was developed through different analysis stages, as shown in Figure 1. In the initial design phase, as shown in Figure 1(a), the FSS incorporates four inward-facing arrow-shaped metallic patches symmetrically arranged at corners of the design. The corresponding reflection coefficient response, represented by the black solid line in Figure 2, exhibits a resonance at 10.5 GHz with an S_{11} value of -8 dB. It exhibits negligible cross-polarized reflection due to its symmetric geometry, which lacks sufficient anisotropy to couple the incident field to the orthogonal polarization. In the modified stage, depicted in Figure 1(b), four arrow-shaped patches are interconnected to form an X-shaped metallic structure. Introducing connecting arms increases effective current path length and enhances electromagnetic coupling between adjacent elements with an extra resonance at 8.4 GHz, as shown by the red line in Figure 2, achieving S_{11} values of -13 dB. The arrow-shaped resonator introduces additional inductive current paths and capacitive cou-

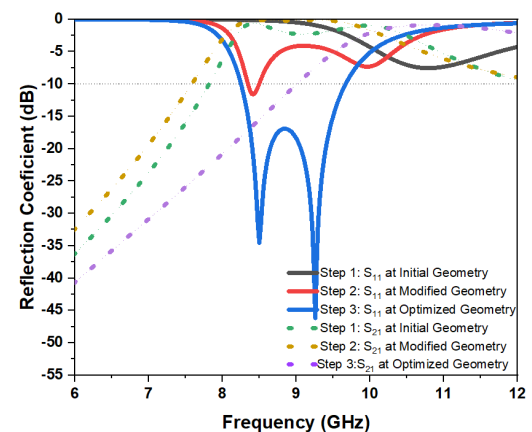


FIGURE 2. Reflection characteristics of the initial, modified, and optimized FSS design.

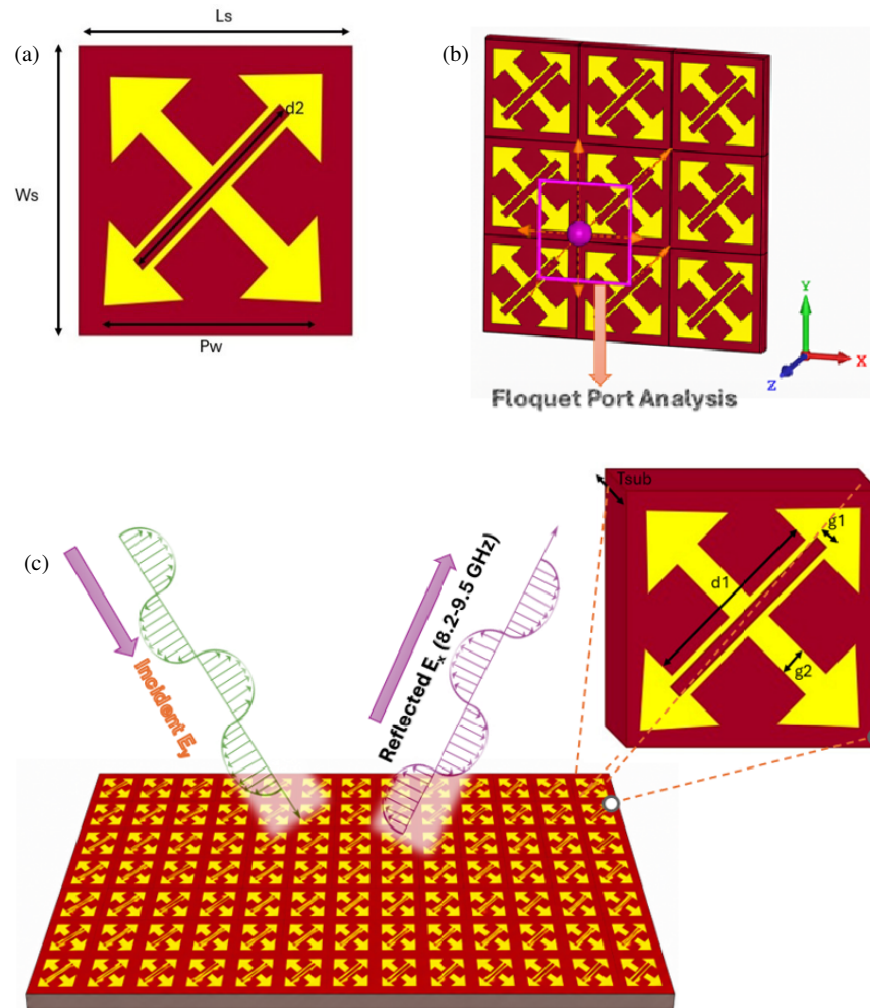


FIGURE 3. Proposed FSS design. (a) Front view, (b) Floquet port analysis, and (c) FSS array analysis.

pling between adjacent metallic sections, producing a distinct resonance around 8.5 GHz. However, the coupling is insufficient to achieve the desired wideband polarization-conversion response. The optimized stage is illustrated in Figure 1(c), which incorporates a diagonal metallic strip of width d_2 across the X-shaped structure. The diagonal strip enhances inductive current paths and capacitive coupling, generating closely spaced resonances whose interaction improves bandwidth and cross-polarized reflection.

Adding this strip further modifies surface current distribution and strengthens the interaction between the incident electromagnetic wave and the corresponding reflection response, represented by the blue solid curve in Figure 2, which demonstrates a minimum S_{11} of -42 dB along with a wideband. The proposed FSS achieves -10 dB PCR, indicating a significant improvement in bandwidth compared to the previous stages.

The proposed FSS is a periodic metallic structure for efficient polarization conversion and manipulation of electromagnetic waves, as shown in Figure 3. In this proposed FSS, inductance is formed by the diagonal strip and arrow-shaped metal lines where surface currents are stored, while capacitance is formed across small gaps (g_1, g_2) and between metal edges where opposite charges are stored. The dimensions were expressed as $L_s = W_s = 7.3$ mm. The effective metallic pattern width

is $P_w = 6$ mm, which defines the horizontal size of the resonating structure with a thickness of $T_{sub} = 1.6$ mm. The geometrical configuration of the proposed unit cell is shown in Figure 3(a). A diagonal metallic strip was incorporated inside the unit cell for efficient polarization manipulation. The effective diagonal length of the incorporated structure was defined as $d_1 = 5.5$ mm, and the extended diagonal portion was $d_2 = 6$ mm. Two optimized gaps, $g_1 = 0.4$ mm and $g_2 = 0.8$ mm, were included for capacitive coupling and resonance optimization.

3. SIMULATION RESULTS FOR PROPOSED FSS

The proposed FSS was analyzed using the full-wave frequency-domain solver in Computer Simulation Technology (CST) Microwave Studio 2021. To accurately emulate an infinitely periodic structure, unit-cell boundary conditions emerged along the transverse directions, with periodic boundaries assigned to the x_{max} , x_{min} , y_{max} , and y_{min} planes. Floquet ports were used along the (z)-axis to excite the structure with plane waves and extract modal scattering parameters. Z_{min} and Z_{max} boundaries were defined as open (add space) boundary conditions to model an unbounded free-space environment and minimize spurious reflections, as shown in Figure 3(b). Tetrahedral mesh discretiza-

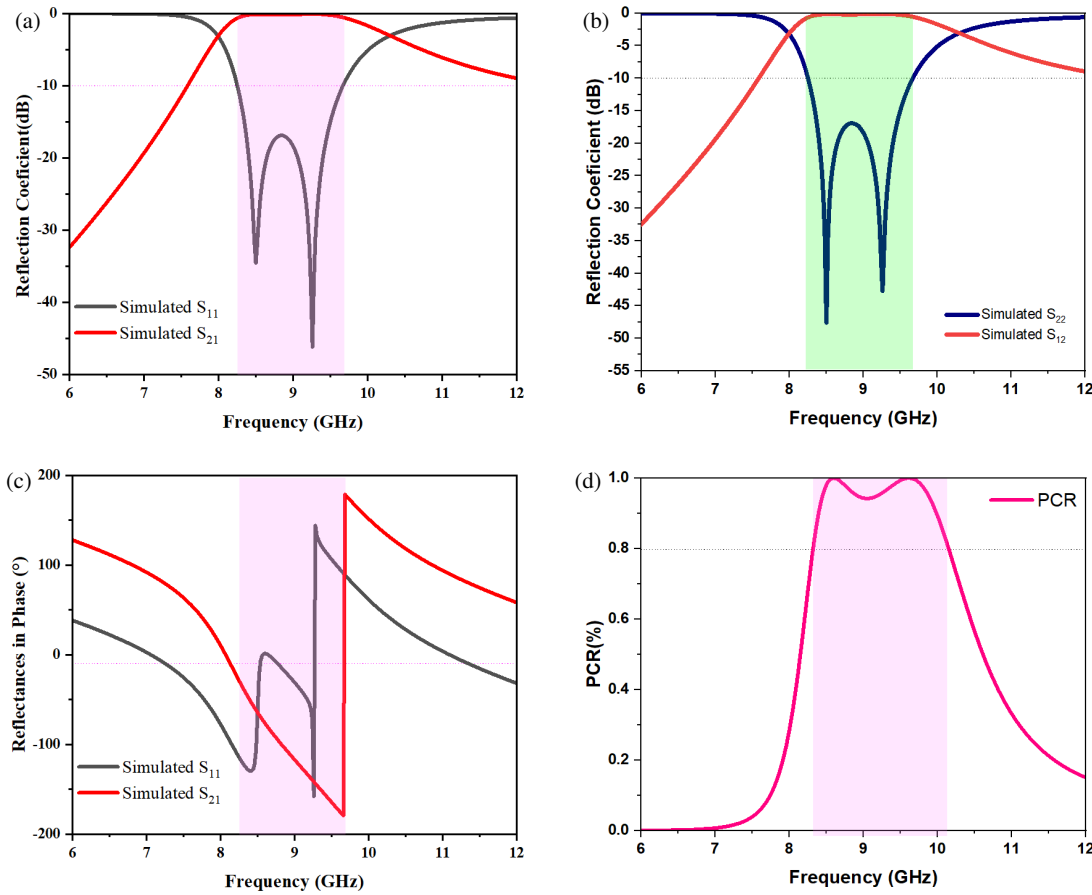


FIGURE 4. Simulated reflection responses toward linearly polarized waves. (a), (b) Cross-polarized and co-polarized reflection characteristics, (c) phase responses, and (d) simulated PCR performance demonstrating the polarization conversion efficiency.

tion combined with adaptive mesh refinement was adopted to ensure the design's numerical stability, convergence, and high computational accuracy. The simulation domain consisted of approximately 42,372 mesh cells with an average mesh quality of 90%. This meshing strategy enabled an accurate resolution of localized electromagnetic fields, resonant surface currents, and near-field interactions responsible for the polarization conversion phenomenon as depicted in Figure 3(c).

Under linearly polarized plane-wave illumination, the FSS's polarization conversion specifications were evaluated using co-polarized and cross-polarized reflection coefficients as shown in Figures 4(a) and (b). The parameters S_{11} and S_{21} represent the co- and cross-polarized reflection responses for x - and y -polarized incident electromagnetic (EM) waves, respectively. These reflection coefficients quantitatively measure the electromagnetic wave transformation process and are used to assess the polarization conversion efficiency, reflection behavior, and overall performance of the proposed FSS.

Linear-to-orthogonal polarization conversion is realized when an incident y -polarized EM wave is transformed into its orthogonal x -polarized counterpart upon reflection from the proposed FSS. Efficient LP-CPC operation is achieved when the magnitude of the cross-polarized reflection coefficient S_{21} exceeds -3 dB, while the co-polarized reflection coefficient S_{11} remains < -10 dB, and vice versa for x -polarized

incidence. Simulated co-polarized and cross-polarized reflection responses under x - and y -polarized excitations are shown in Figure 4(a) and Figure 4(b). It can be represented that the co-polarized reflection coefficients S_{11} & S_{22} are suppressed below -10 – -10 dB, whereas cross-polarized reflection coefficients S_{12} & S_{21} remain -1 dB over the frequency of 8.2–9.5 GHz. The observed relative phase shift of $\approx \pm 180^\circ$ demonstrates the effective conversion of the incident linear polarization into its orthogonal counterpart, as shown in Figure 4(c). These results confirm the strong polarization-conversion capability of the proposed FSS within the 8.2–9.5 GHz frequency.

To comprehensively understanding the polarization conversion mechanism, the Cartesian coordinate system (x, y) was rotated clockwise by 45° to obtain a new orthogonal coordinate system (u, v), as highlighted in Figures 5(a) and (b). An incident linearly polarized wave propagating along the z -direction appears to be decomposed into two equal components along the u - and v -axes [30, 31]. The incident electric field is expressed as (1)

$$\vec{E}_{inc} = \frac{\sqrt{2}}{2} E_{inc} \cdot e^{jkz} \hat{u} + \frac{\sqrt{2}}{2} E_{inc} \cdot e^{jkz} \hat{v} \quad (1)$$

The scattered electric field contains both co-polarized and cross-polarized components, which can be written as (2)

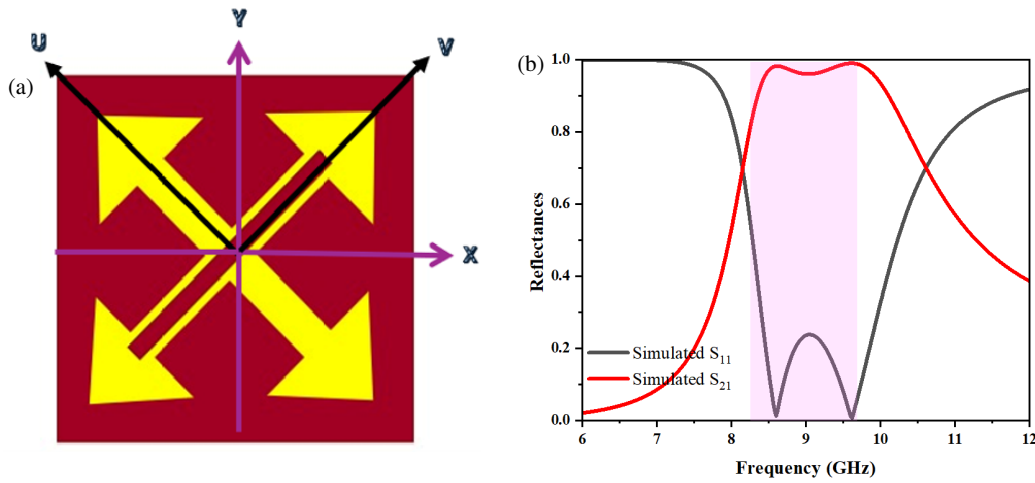


FIGURE 5. (a) Geometry of the u - v coordinate system and (b) reflection coefficient magnitude.

$$\begin{aligned} \vec{E}_{ref} &= \frac{\sqrt{2}}{2} \left[r_{uu} E_{inc} \cdot e^{j(-kz + \phi_{uu})} + r_{uv} E_{inc} \cdot e^{j(-kz + \phi_{uv})} \right] \hat{u} \\ &+ \frac{\sqrt{2}}{2} \left[r_{vv} E_{inc} \cdot e^{j(-kz + \phi_{vv})} + r_{vu} E_{inc} \cdot e^{j(-kz + \phi_{vu})} \right] \hat{v} \quad (2) \end{aligned}$$

where r_{ab} ($ab = uv$) and ϕ_{ab} denote reflection coefficients and corresponding reflection phases, respectively. Because the cross-polarized reflection coefficients r_{uv} and r_{vu} are negligible, Eq. (3) can be simplified as

$$\vec{E}_{ref} = \frac{\sqrt{2}}{2} r_{uu} E_{inc} \cdot e^{j(-kz + \phi_{uu})} \hat{u} + \frac{\sqrt{2}}{2} r_{vv} E_{inc} \cdot e^{j(-kz + \phi_{vv})} \hat{v} \quad (3)$$

The phase difference between reflected components is given in (4)

$$\phi_{\text{difference}} = \phi_{uu} - \phi_{vv} = \pi + 2k\pi, \quad k \in \mathbb{Z} \quad (4)$$

indicating a phase difference of approximately 180° . High reflection magnitudes of r_{uu} and r_{vv} , together with this phase condition, cause the polarization direction of the reflected wave to rotate by 90° . Consequently, efficient polarization conversion is achieved using Eq. (5).

$$\text{PCR} = \frac{|S_{\text{cross}}|^2}{|S_{\text{cross}}|^2 + |S_{\text{co}}|^2} = \frac{|S_{21}|^2}{|S_{21}|^2 + |S_{11}|^2} = \frac{|S_{12}|^2}{|S_{12}|^2 + |S_{11}|^2} \quad (5)$$

The simulated PCR characteristics are presented in Figure 4(d). The PCR reaches nearly $> 99\%$ at a resonant frequency of 8.2–9.5 GHz, demonstrating almost complete conversion of the incident y -polarized wave to a scattered x -polarized wave, and vice versa. Moreover, PCR remains $> 99\%$ throughout the frequency band of 8.2–9.5 GHz, indicating a wide band and highly efficient polarization conversion.

4. PARAMETRIC ANALYSIS OF KEY GEOMETRICAL PARAMETERS AND OBLIQUE INCIDENCE ON POLARIZATION CONVERSION PERFORMANCE

The polarization conversion performance of the proposed FSS is strongly influenced by its geometric parameters. To investigate their effects, parametric analysis of $L_s = W_s$, g_1 and g_2 was performed, as illustrated in Figures 6(a), (b), and (c). Among these parameters, unit-cell length and width significantly affect resonant characteristics. Variations in $L_s = W_s = 6.8$ mm to 7.4 mm shift the resonance from 8.2 GHz–9.5 GHz to 8.6 GHz to 10 GHz and the corresponding frequency linear-to-orthogonal polarization band toward higher frequencies and noticeable reduction in bandwidth with PCR approximately 85%–99%.

To further clarify the design mechanism, a parametric analysis was carried out by varying gap dimensions while keeping remaining structural parameters unchanged. The corresponding PCR characteristics are presented in Figures 6(b) and (c). As shown in Figure 6(b), the gap was varied from 0 to 0.4 mm. At $g_1 = 0$ mm, the polarization conversion is negligible, indicating that the gap is essential for generating the required anisotropic response. Increasing g_1 enhances the PCR by exciting two resonant modes. At the optimized value of $g_1 = 0.2$ mm, effective coupling between these modes produces a broad high-PCR band. Further increasing g_1 to 0.3–0.4 mm shifts the resonances and reduces the PCR in the intermediate region. Therefore, g_1 of 0.2 mm is selected for broadband linear-to-orthogonal polarization conversion. Similarly, Figure 6(c) shows the effect of g_2 , varied from 0.1 to 0.6 mm. Increasing g_2 shifts the lower resonance toward higher frequencies, while the upper resonance remains relatively stable. This behavior is attributed to the change in capacitive coupling between metallic elements. A larger g_2 reduces the effective capacitance, resulting in a higher resonant frequency. An optimized value of g_2 is 0.6 mm, which provides better coupling between resonant modes and maintains a high PCR over the desired operating band of 8.2–9.5 GHz.

Angular stability can be evaluated under both normal and oblique incidences. The structure maintains excellent polariza-

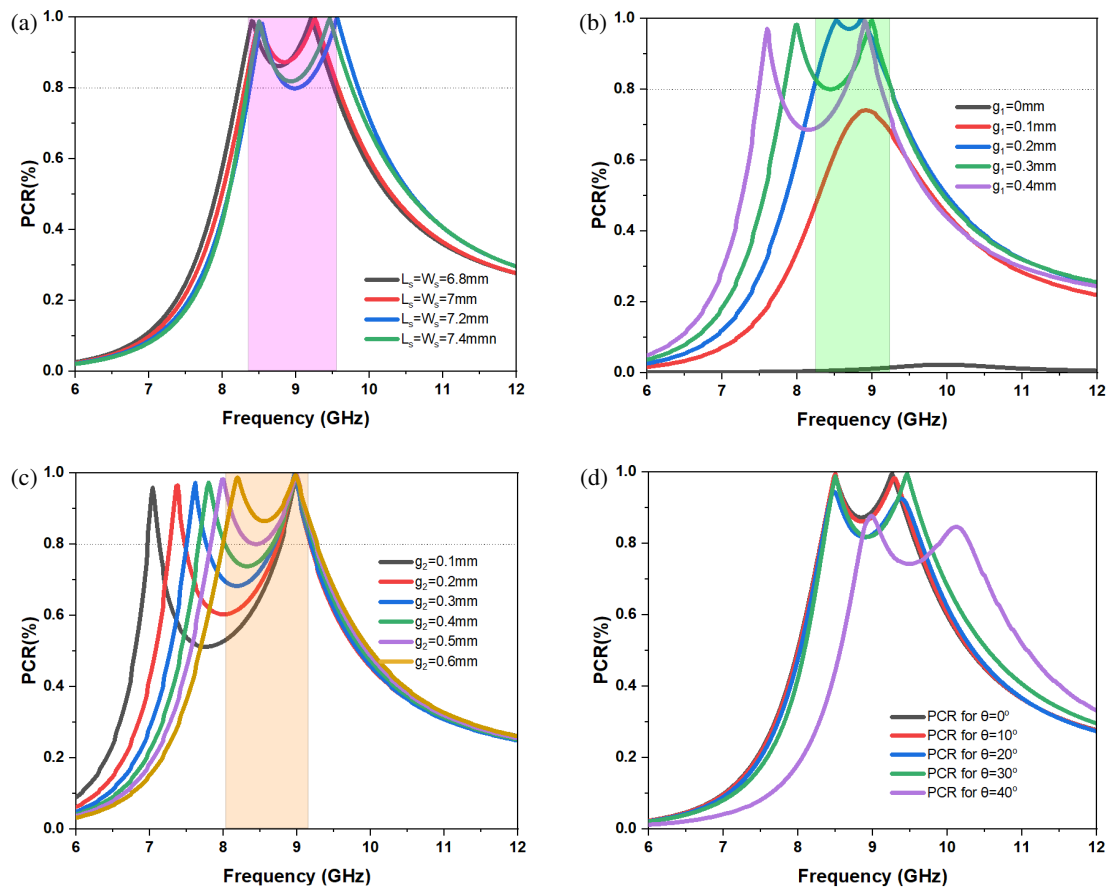


FIGURE 6. PCR for (a) parametric analysis of $L_s = W_s$ from 6.8 mm–7.4 mm, (b) PCR for θ varies from 0° – 40° , (c) parametric analysis of g_1 from 0–0.4 mm, and (d) parametric analysis of g_2 from 0.1–0.6 mm.

tion conversion performance, with PCR exceeding 80%–95% up to an incidence angle of 40° in the operating frequency band. We can observe frequency shifts from 8.2–9.5 GHz to 9 GHz to 10.5 GHz, as shown in Figure 6(d). As the incidence increases, the co-polarized reflection component decreases, and the conversion bandwidth decreases slightly; however, the PCR remains above 80% in the 8.2–9.5 GHz. A reduction in bandwidth and conversion efficiency is observed due to wavelength-dependent resonance shifts and increased scattering effects at oblique incidence angles. Nevertheless, the PCR remained above 95% within 8.2–9.5 GHz up to 40° incidence. These findings show that the proposed FSS has strong angular stability, making it suitable for real-world radar and wireless communication applications.

5. CURRENT DISTRIBUTION ANALYSIS

The surface current distributions at 8.2–9.5 GHz reveal the resonant behavior responsible for the polarization conversion characteristics of the proposed FSS, as shown in Figure 7. At both frequencies, strong surface currents are predominantly concentrated along the diagonal metallic strips, indicating that these resonating elements play a major role in the structure's electromagnetic response. The maximum current density was observed near the central diagonal region and along inclined arms, demonstrating a strong interaction between the incident

electromagnetic wave and the resonator. The corner sections also support induced currents, contributing to the overall current path and electromagnetic coupling within the unit cell. Furthermore, current vectors exhibit both parallel and anti-parallel flow characteristics in adjacent resonating sections, leading to the simultaneous excitation of electric and magnetic resonances.

Antiparallel current paths generate confined magnetic fields between neighboring conductors, whereas parallel currents contribute to electric dipole resonance. The coexistence of these resonant modes produces orthogonal current components with different phase responses, allowing the incident linearly polarized wave to be transformed into an orthogonal polarization state. Therefore, observed current distributions at 8.2–9.5 GHz confirm that the polarization conversion mechanism is governed by the combined effect of electric and magnetic resonances supported by the diagonal resonating structure.

6. PROTOTYPE FABRICATION AND EXPERIMENTAL CHARACTERIZATION

Experimental validation was conducted to assess the practical performance of the proposed FSS under realistic operating conditions. For this purpose, a finite-array prototype consisting of 22×22 unit cells with an overall aperture size of

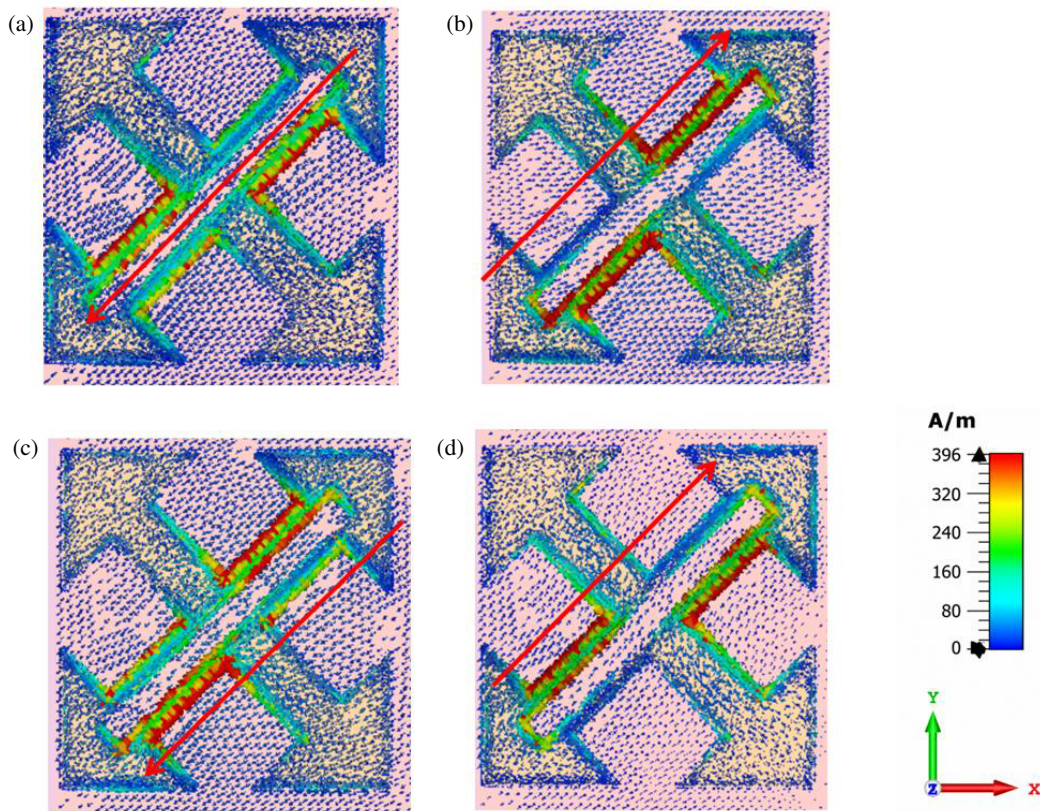


FIGURE 7. Surface current analysis at different frequencies: (a) 8.5 GHz, (b) 8.6 GHz, (c) 9.15 GHz, and (d) 9.25 GHz.

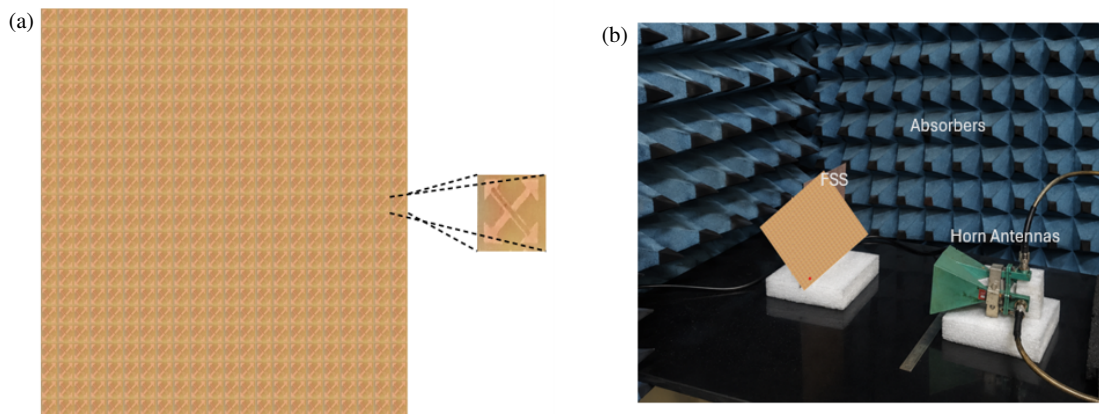


FIGURE 8. (a) Fabricated prototype and (b) measurement setup.

$160 \times 160 \text{ mm}^2$ was fabricated on a 1.6-mm-thick FR-4 dielectric substrate using a high-precision photolithographic printed circuit board (PCB) fabrication process. The fabricated FSS prototype was experimentally characterized using a free-space measurement setup, as illustrated in Figures 8(a) and (b). The measurement system employed a pair of broadband horn antennas (X-band) that served as transmitting (Tx) and receiving (Rx) antennas. To minimize edge diffraction and emulate an infinite periodic structure, the fabricated sample was mounted within the aperture of a $6\lambda \times 6\lambda$ metallic aluminium screen. The Tx and Rx antennas were positioned at 2 meters from the prototype, satisfying the Fraunhofer far-field criterion [32] and ensuring plane-wave illumination.

For cross-polarization measurements, the transmitting antenna was rotated by 90° relative to the receiving antenna. Two ridged horn antennas were connected to a calibrated FMA N9917A Vector Network Analyzer (VNA) to accurately record the reflection and transmission characteristics of the proposed FSS. Furthermore, to investigate the design's angular stability, the prototype assembly was rotated by 10° , 20° , and 40° in the azimuth plane while maintaining the measurement geometry. The measured results validate the stable electromagnetic response of the proposed structure under oblique incidence. Figures 9(a) and (b) compare simulated and measured reflection and transmission responses of the proposed FSS. The measured results show good agreement with the simulations, validating

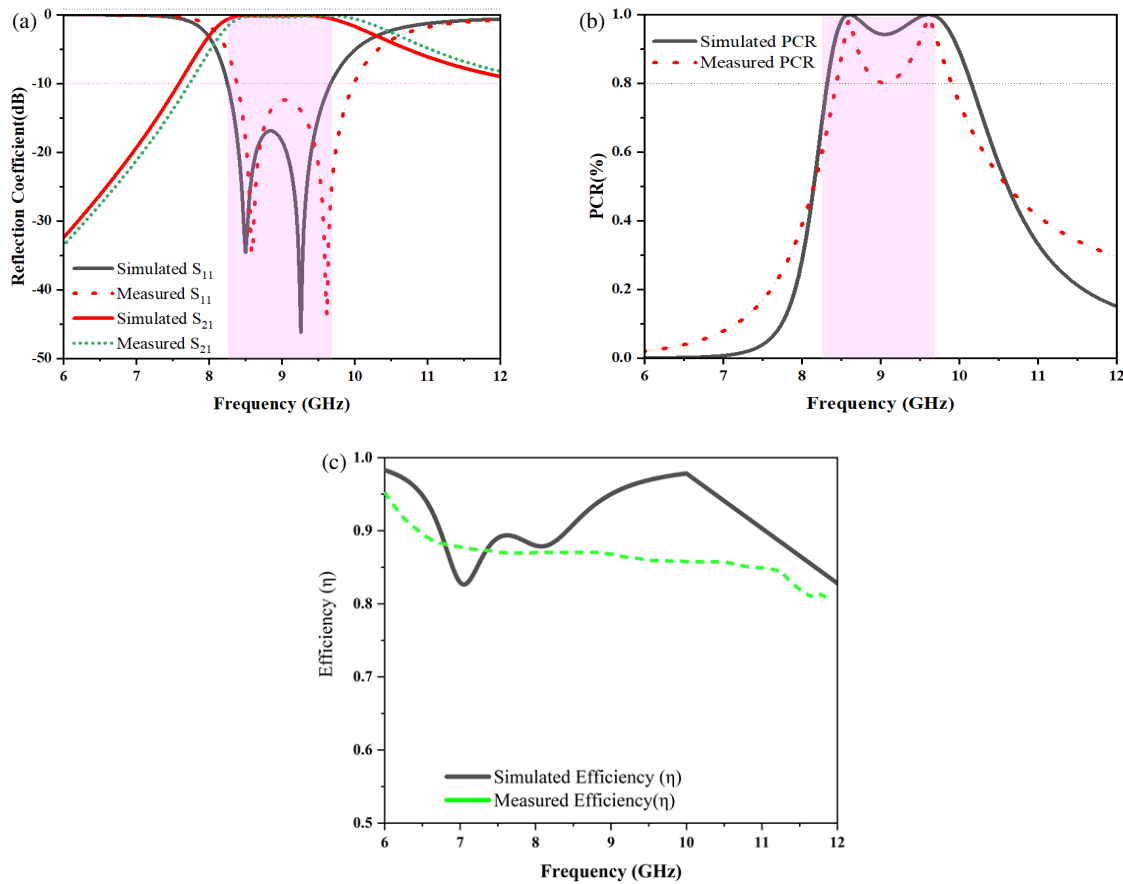


FIGURE 9. Comparison of measured and simulated (a) reflectance characteristics, (b) PCR, (c) efficiency.

the design performance. Minor discrepancies were attributed to fabrication tolerances, finite prototype dimensions, and measurement uncertainties.

Simulated and measured reflection coefficients and PCR are compared in Figure 9(b). The two results exhibit similar trends over the operating band of 8.2–9.5 GHz, confirming linear-to-cross polarization conversion behavior of the proposed FSS. The measured operating band is (8.4–9.7 GHz), compared with the simulated band of 8.2–9.5 GHz, corresponding to a bandwidth deviation of approximately (0.2%). The small discrepancies between simulated and measured results can be attributed to fabrication tolerances, variations in the dielectric properties of the FR-4 substrate, finite-array effects, antenna alignment, and uncertainties associated with the free-space measurement setup. Overall, measured results validate the high-efficiency polarization-conversion performance of the proposed FSS in the X-band.

The reflection efficiency η is defined as the ratio of the total reflected power to the incident power and is expressed as

$$\eta = |S_{xy}|^2 + |S_{yy}|^2, \quad (6)$$

where S_{xy} and S_{yy} denote the cross- and co-polarized reflection coefficients, respectively [33]. A value of η close to unity indicates that most of the incident electromagnetic power is reflected with minimal dissipative loss. As illustrated in Figure 9(c), the suggested design offers a high conversion efficiency over the X-band frequency range of 8.2–9.5 GHz, with

values approaching 0.98, according to simulated and measured PCR values.

The similarity between simulated and measured values validates the proposed design for detection applications. In target-detection radar systems operating within the X-band frequency range (8.2–9.5 GHz), polarization conversion can significantly improve target discrimination and electromagnetic-wave manipulation. The proposed FSS increases the cross-polarized component S_{yx} and decreases the co-polarized reflection coefficient S_{xx} . Consequently, the reflected wave underwent a 90° polarization rotation, converting the incident y -polarization into x -polarization. At 8.5 and 9.3 GHz, maximum polarization conversion efficiency is attained, where cross-polarized reflection becomes dominant, enabling effective polarization manipulation potentially useful for polarization-diverse and radar target detection applications.

Table 1 presents a comprehensive comparison of the proposed FSS with previously reported polarization-conversion structures in terms of unit-cell area, substrate characteristics, operating bandwidth, fractional bandwidth (FBW), polarization conversion ratio (PCR), conversion functionality, angular stability, mode of operation, and absolute bandwidth. The structures reported in [20, 30, 31] primarily demonstrate linear-to-linear polarization conversion, whereas [32] demonstrates linear-to-circular polarization conversion. In contrast, the works in [6, 13, 15] provide both linear-to-circular and linear-to-cross polarization conversions over different operating

TABLE 1. Comparing the proposed FSS's performance to recently published cutting-edge polarization converter designs in the literature.

Ref.	Unit Cell Area (λ^2)	Dielectric Substrate/ Thickness	Operating Bandwidth	Fractional BW/ PCR (%)	Polarization Conversion	Angular Stability	Mode of Operation	Absolute Bandwidth
[6]	$0.0130\lambda^2$	FR-4/1 mm	24.50–40.32 GHz	48.81%/ $> 90\%$	Linear-to-Circular & Linear-to-Cross	45°	Reflection and Transmission	Wideband
[13]	$0.323\lambda^2$	FR-4/3.2 mm	5.6–6.5 GHz & 9.6 to 11.9 GHz	$> 95\%$	Linear-to-Circular & Linear-to-Cross	30°	Reflection	Narrow band
[15]	$0.013\lambda^2$	FR-4/1 mm	3.08–25.13 GHz	63.07%/PCR $> 90\%$	Linear-to-Circular & Linear-to-Cross	45°	Reflection	Wideband
[20]	$0.0112\lambda^2$	FR-4	5–11 GHz	10.81 GHz $> 89\%$	Linear-to-linear	Not Reported	Reflection	Wideband
[34]	Not Reported	Not Reported	Not Reported	$\sim 100\%$	Linear-to-Linear	Not Reported	Reflection	Narrow band
[35]	Not Reported	FR-4	8.05–18.33 GHz	77.8%/ $> 90\%$	Linear-to-Linear	45°	Reflection	Wideband
[36]	$0.265\lambda_0$	FR-4	8–14 GHz	64%/ $\approx 97\%$	Linear-to-Circular	40°	Reflection	Wideband
[37]	$0.13\lambda_0$	Rogers 5880	9.72–10.00, 17.65–41.87, 45.67–45.80, 49.66–49.84 GHz	98.72%/PCR $\geq 90\%$	Linear-to-Linear Linear-to-Circular	45°	Reflection	Narrow and Wideband
Proposed work	$0.13\lambda_0$	FR-4	8.2–9.5 GHz	14.69%/98%	Linear $\rightarrow$ Cross	40°	Strong Reflection	Wideband

bands. The recently reported structure in [33] exhibits both linear-to-linear and linear-to-circular polarization conversion with a high fractional bandwidth and angular stability up to 45° . Although several reported structures exhibit broader operating bandwidths, the proposed FSS provides highly efficient linear-to-cross polarization conversion with a PCR exceeding 98% over the 8.2–9.5 GHz X-band, corresponding to a fractional bandwidth of 14.69%. Furthermore, the proposed single-layer low-cost FR-4 structure maintains stable polarization-conversion characteristics for oblique incidence angles up to 40° . Therefore, the proposed design offers a useful combination of high PCR, X-band operation, angular stability, and a simple reflective configuration for polarization-manipulation applications.

7. CONCLUSION

A wide-band polarization converter incorporating a diagonal strip and arrow-shaped metal lines was proposed and systematically investigated using theoretical analysis and full-wave simulations. The numerical results revealed that the converter's polarization conversion ratio was greater than 98%, within the 8.2–9.5 GHz frequency range, providing a wide operational bandwidth of 1.3 GHz. The device also exhibited satisfactory angular stability, maintaining efficient performance for angles of incidence between 0° and 40° . Moreover, the polarization conversion mechanism was comprehensively examined through surface-current distribution analysis, offering valuable insights into the electromagnetic characteristics of the proposed structure. In modern communication and sensing applications,

where wide-band functionalities are often required, a unified reflector that can convert polarization from linear to cross polarization provides a compact and effective solution.

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